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Miettinen, Jenni

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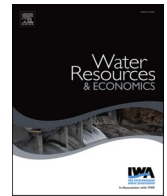
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Cost function approach to water protection in forestry

Jenni Miettinen^{a,*}, Markku Ollikainen^a, Mika Nieminen^b, Lauri Valsta^c

^a University of Helsinki, Department of Economics and Management, P.O. Box 27, 00014, University of Helsinki, Finland

^b Natural Resources Institute Finland, Latokartanonkaari 9, 00790, Helsinki, Finland

^c University of Helsinki, Department of Forest Sciences, P.O. Box 27, 00014, University of Helsinki, Finland

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ABSTRACT

The European Water Framework Directive (WFD) strongly emphasizes that all water polluting sectors must enhance the protection of water bodies in a cost-effective way. River Basin Management Plans need to be made to achieve a good environmental status for all water bodies by 2027 at the latest. This article examines three principal water protection measures used in forestry: buffer zones, overland flow fields and sedimentation ponds. We analytically develop marginal abatement cost functions for each of these measures and apply them numerically for the Finnish forestry. We find that the marginal abatement costs of nutrients using buffer zones in clear-cut mineral soil forests are very high, as they entail leaving financially mature and uncut trees. In contrast, the marginal costs of using overland flow fields in conjunction with ditch cleaning and clear-cutting in peatlands are very low. Furthermore, for sediments using overland flow fields as a water protection measure entails significantly lower abatement costs than does using sedimentation ponds in conjunction with ditch cleaning in peatland forests. A cost-effective solution in a river basin entails that the highest nutrient reductions are made in agriculture but that forestry also does its share. A cost-effective allocation of abatement measures entails that the proportions of the overall nutrient reduction are 3% (1%) in forestry and 97% (99%) in agriculture when the reduction target is set as 10% (30%).

1. Introduction

The European Water Framework Directive (WFD) requires that member states take actions to reach good environmental status of all water bodies by 2027 at the latest. The key tools for achieving this goal are River Basin Management Plans. In these plans, member states design actions and policies requiring all polluting sectors to reduce their effluents. The allocation of nutrient reductions between sectors should follow the principle of cost-effectiveness, which means achieving the required reduction of nutrient loading with minimum costs. In its simplest form, cost-effectiveness requires that the marginal abatement costs of different sectors (and agents) are equalized for any target level of water quality. For regional pollutants, such as nutrients in waterways, this rule is modified into a requirement that the marginal abatement costs of reducing pollution at any given receptor point are equalized between all polluters. Thus, one must account for the transfer of nutrients from the source to the receptor points [1].

The main polluting sectors in Finland are agriculture and municipal waste waters. The current estimate of the forestry-induced nitrogen load is 1600 Mg year⁻¹, and the phosphorus load is 130 Mg year⁻¹. They constitute only approximately 5% of the total

* Corresponding author.

E-mail addresses: jenni.miettinen@helsinki.fi (J. Miettinen), markku.ollikainen@helsinki.fi (M. Ollikainen), mika.nieminen@luke.fi (M. Nieminen), lauri.valsta@helsinki.fi (L. Valsta).

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load of nitrogen and 8% of the total phosphorus load in Finland [2]. Recent studies by Nieminen et al. [3] indicate, however, that peatlands drained for forestry (5 Mha, or 20% of the land cover) provide significantly larger nitrogen and phosphorus loads than do pristine peatlands. Thus, forestry may account for a 10- to 15-times larger proportion of the total loads than previously estimated [4]. Furthermore, in Finland, forestry is an exceptionally high source of sediments due to forest drainage in peatlands.

The main sources of nutrient and sediment loads from forest management are clear-cutting, site preparation, fertilization and ditching [e.g., 5, 6, 7]. While in mineral soils, the source of the nutrient load is predominantly clear-cutting, ditch cleaning and clear-cuts are the sources of the nutrient and sediment loads in drained peatland forests. A typical water protection measure in mineral soils is the use of buffer zones, which are unharvested land areas between the clear-cut area and waterway [5,8,9]. In peatlands, sedimentation ponds, overland flow fields and other measures, such as sedimentation pits and ditch breaks, are used to mitigate increased loading [e.g., 10, 11, 12, 13, 14, 15].

For well-designed River Basin Management Plans, the member states need information on nutrient reduction costs in forestry in the same manner as provided, for instance, in wastewater treatment plants [16] or agriculture [17–19] or [20]. This helps in comparing the marginal abatement costs in forestry with those in other polluting sectors. Unfortunately, well-developed estimates of marginal abatement costs for forestry are missing, making designing cost-effective policies difficult.

The aim of our study is to fill this gap in the knowledge and to develop marginal abatement costs of the three most frequently applied water protection measures in forestry: buffer zones, sedimentation ponds, and overland flow fields. To our knowledge, this study is the first of its kind in forest economics. Given that forest management decisions relating harvesting and water protection are made infrequently (over tens of years in boreal forests), we do not start with bare land but instead postulate an initial stand and let the forest landowner decide upon forest management and harvesting, as well as water protection measures. We derive the analytical features of marginal abatement cost functions in forestry and then apply them numerically using Finnish data on forest management, focusing on water protection measures. We define the marginal abatement costs of water protection measures in forestry at the time when these measures are implemented.

We then put the derived marginal abatement cost functions in action and examine how to allocate abatement in a cost-effective way between agriculture and forestry. The model comprises both nutrients: nitrogen and phosphorus. The comparison of the marginal abatement costs of nutrients in forestry to the respective costs in other sectors, especially in agriculture, provides a special challenge, because the management decisions in forestry and agriculture differ. Unlike in forestry, in agriculture, most water protection measures are chosen every year as a part of cultivation decisions. Furthermore, the nutrient and sediment loads from single harvesting or ditching decisions may last even longer than ten years [2], while in agriculture, most nutrient loads depend mainly on annual decisions. Nevertheless, the approach taken in deriving the marginal abatement costs provides an adequate basis for the allocation of water protection measures between agriculture and forestry, as we solve the cost-efficient solution for agriculture and for annually harvested or treated forest land.

The only previous study resembling our research is by Lauren et al. [21], who calculated the unit cost of nitrogen reduction using buffer zones. To our knowledge, there are no earlier studies on the marginal abatement costs of reducing sediment loads in forestry. Previous economic studies focusing on forestry and water protection from viewpoints other than cost-effectiveness are found in Miller and Everett [22]; Matero [23–25]; Matero and Saastamoinen [26]; Creedy and Wurzbacher [27]; Sun [28]; Eriksson [29], Miettinen et al. [30] and Hökkä et al. [31]. Our approach follows that of Miettinen et al. [30,32], who were the first to include nutrient load damage in the Faustmann rotation model. Analyses focusing on the cost-effectiveness of non-point-source pollution in river basins in Finland are scarce. The cost-effective reduction of phosphorus discharging from agricultural land, forestry land, scattered settlements, and peat mining at the catchment scale was analyzed by Hjerpe and Väisänen [33]. Lankoski et al. [34] used a river basin model to analyze trading between point and non-point sources, but they did not include forestry in their analysis.

The rest of the study is organized as follows. First, we analytically present the marginal abatement cost functions for water protection measures used in forestry. Second, we provide the numerical marginal abatement costs at various levels of nutrients and sediment abatement in forestry. Third, based on the marginal abatement cost functions of nutrients, we develop a river basin application and analyze the cost-effective solution, including agriculture and forestry as polluting sectors.

2. Marginal abatement functions of water protection measures for forestry

The marginal abatement cost function describes how abatement costs increase when abatement is increased by one unit. We focus on water protection measures to reduce nutrient loads from clear-cuts in mineral soils (buffer zones) and ditch cleaning and clear-cuts in drained peatland forests (overland flow fields). We restrict our analysis to short-term marginal abatement costs, meaning that we consider one rotation period.

2.1. Marginal abatement costs of nutrients in mineral soils

Consider an even-aged stand of trees growing on mineral soil adjoining a watercourse. Let the initial stand age be A . The stand is clear-cut, and a buffer zone is left between the clear-cut area and the downstream watercourse. A buffer zone is often left uncut, but partial harvesting is also possible.¹ We assume that no trees are harvested from the buffer zone. The time of clear-cutting at the end of

¹ In Finland, the national forest laws and forest certification system (FFCS) allows partial harvesting in the buffer zone. The FSC certification system requires that the buffer zone is left unmanaged.

the rotation period is denoted by T , and the length of time until clear-cutting is $T - A$. The growth function is denoted by $f(T - A)$. Let the timber price be p and the real interest rate be r . We denote the share of the buffer zone relative to the total forest stand area as m . In the absence of water protection, the harvest revenue under the given rotation age is $pf(T - A)$, and under the established buffer zone, it is $(1 - m)pf(T - A)$, indicating that the buffer zone decreases the harvested forest area and that the lost harvest revenue constitutes the abatement costs of buffer zones as a function of the nutrient reduction target.

The nutrient load from a clear-cut area starts after clear-cutting, and the loading is assumed to last for a fixed period of time x years. The nutrient load after clear-cutting, $H(s)$, is a function of time, s . The buffer zone fixes nutrients released from the clear-cut area into the zone, and we express the share of the nutrient load reduction as a function of the size of the buffer zone by $g(m)$, which is a concave function in m ($g_m > 0$ but $g_{mm} < 0$), indicating that the buffer zone has a decreasing ability to fix nutrients. Thus, the reduction of nutrients is given by $g(m)H(s)$.

We assume that the forest landowner focuses on the sum of the nutrient loads from years after clear-cutting, because controlling annual loads is not feasible in practice, as a buffer zone is established once and becomes permanent. Thus, we integrate over time to sum the nutrient loads and let \bar{z}_m denote the upper limit on nutrient loads set by society, such that the periodic loads from clear-cutting cannot exceed it: $\bar{z}_m \geq \int_0^x [1 - g(m)]H(s)$ (subscript m refers to mineral soils). Then, the objective of the landowner is to choose the optimal (single) rotation period and the optimal size of the buffer zone to maximize the harvest revenue, subject to the constraint on the upper limit on emissions:

$$\text{Max } (1 - m)pf(T - A)e^{-r(T-A)} \quad \text{s.t.} \quad \bar{z}_m \geq \int_0^x [1 - g(m)]H(s)$$

This constrained optimization problem is conveniently solved by forming a Lagrangian function, L , where the Lagrangian multiplier λ links the objective function and the constraint, thus providing the shadow price of the environmental quality. The Lagrangian function is as follows²:

$$L = (1 - m)pf(T - A)e^{-r(T-A)} + \lambda \left\{ \bar{z}_m - \int_0^x [1 - g(m)]H(s) \right\} e^{-r(T-A)} \quad (1)$$

The choice of the optimal rotation period and the size of the buffer zone can be characterized by the following first-order conditions:

$$L_T = (1 - m)[pf_T(T - A) - rpf(T - A)] - r\lambda \left\{ \bar{z}_m - \int_0^x [1 - g(m)]H(s) \right\} = 0 \quad (2)$$

$$L_m = -pf(T - A) + \lambda \left\{ \int_0^x g_m(m)H(s) \right\} = 0 \quad (3)$$

$$L_\lambda = \bar{z}_m - \int_0^x [1 - g(m)]H(s) = 0 \quad (4)$$

From equation (3), we obtain $pf(T - A) = \lambda \left\{ \int_0^x g_m(m)H(s) \right\}$, and substituting in (2) gives $\lambda = \frac{pf_T(T-A)}{r \int_0^x g_m(m)H(s)} > 0$. Thus, λ is positive and indicates the marginal abatement cost at the given upper limit on loads. This marginal abatement cost depends on the ratio of the marginal harvest revenue lost by increasing the size of the buffer zone by one unit over the marginal reduction in nutrient loading. Equation (4) simply requires that the upper limit on the nutrient load is binding, that is, the loads are equal to the limit, $\int_0^x [1 - g(m)]H(s) = \bar{z}_m$. By equation (4), equation (2) shows that the optimal rotation age is determined independently of the nutrient load constraint and the buffer zone size.

The second-order conditions for the problem hold and are given in [Appendix A](#). Thus, we can use comparative statics to examine how exogenous variables impact the optimal rotation age, the size of the buffer zone and the marginal costs of establishing it. First, we have that $\frac{\partial m}{\partial z_m} < 0$ and $\frac{\partial \lambda}{\partial z_m} < 0$, indicating that an increase in the upper limit on the nutrient load allows higher loads and decreases the buffer zone and the marginal abatement costs of nutrients. The effect of the upper limit of the nutrient load on the optimal rotation age is ambiguous. For an increase in timber price, we have that $\frac{\partial T}{\partial p} < 0$, $\frac{\partial m}{\partial p} = 0$ and $\frac{\partial \lambda}{\partial p} > 0$. Thus, the impact of the timber price on the optimal rotation age is conventional. A higher timber price does not change the size of the buffer zone, because the upper limit on the nutrient load is binding and the size of the buffer zone cannot be changed. Instead, a higher timber price increases the marginal abatement costs. Finally, $\frac{\partial T}{\partial r} < 0$, $\frac{\partial m}{\partial r} = 0$ and $\frac{\partial \lambda}{\partial r} < 0$. Similar to the case for the timber price, the effect of the real interest rate on the

² Formulation of the problem in equation (1) means that the nutrient load constraint is binding at the time of the clear-cutting. Alternatively, the Lagrangian function could be formulated as $L = (1 - m)pf(T - A)e^{-r(T-A)} + \lambda \{ \bar{z}_m - [\int_0^x [1 - g(m)]H(s)]e^{-r(T-A)} \}$, when the nutrient load constraint is binding at all periods of time and the present value of future nutrient loads is not allowed to exceed the constraint. When the problem is formulated as in equation (1), the nutrient load reduction is reached using only the buffer zone. The alternative formulation of the problem means that both postponing rotation age and the buffer zone can be used to decrease the nutrient loads from clear-cutting. In both cases, the λ is a function of the same parameters.

optimal rotation age is conventional, and it does not have any impact on the optimal size of the buffer zone. However, a higher interest rate decreases the optimal marginal abatement costs of nutrients, as seen from the above definition of λ . As the marginal benefit of increasing the size of the buffer zone by one unit increases, the optimal marginal abatement costs of nutrients decrease.

In summary, the marginal abatement cost function is defined by $MAC = \lambda(\bar{z}_m, p, r)$. For given timber prices and real interest rates, the MAC-curve increases as the upper limit on the nutrient load tightens. Note, finally, that under some regularity assumptions, the cost functions represent the underlying production technology [35], so that these functions can be applied to guide the choice of water protection measures in the river basin model in section 4.

2.2. Marginal abatement costs of mitigating nutrient exports in drained peatland forests

Consider now a forest stand on a peatland adjoining a watercourse. Stand management requires ditch cleaning, because the drainage capacity of the ditches weakens over time and seriously reduces the growth of the stand.³ Ditch cleaning causes nutrient loading, which is expected to last for approximately 10 years [2]. When the stand becomes financially mature and is harvested, clear-cutting is an additional source of nutrient loads. An overland flow field is used as a water protection measure to reduce the nutrient loads from ditch cleaning and clear-cutting. Overland flow fields are pristine or restored mires over which the discharge waters from the upstream drained catchment are conveyed [36,37].

Suppose again that the forest landowner has an initial stand of age A . The time of clear-cutting is denoted by T , and the length of time until clear-cutting is $T - A$. Forest growth depends also on the ditch cleaning effort n . Ditch cleaning is performed at time A after the first commercial thinning of the stand, and the growth function is denoted by $f(T - A; n)$ [38,39].⁴ Let the unit cost of ditch cleaning be w , while γ denotes the unit cost of the overland flow field. The size of the overland flow field is denoted by B , and the upper limit on the loads is \bar{z}_p (subscript p refers to peatlands). The nutrient loading from ditch cleaning is $K_D(s, n)$ and that after the clear-cut is $K_C(s, n)$. Nutrient loading from both sources is assumed to last for the same x years, and we again integrate over time to sum the nutrient loads for years following the forest management methods. The nutrient reduction as function of the size of the overland flow field is $g(B)$. We assume that this function is concave in B , with a positive first and negative second derivative. The overland flow field is established at the time of ditch cleaning, but its size is chosen by also accounting for loading after the clear-cut at the end of the rotation period. Thus, the reduction of nutrients from both sources as a share of the original load is defined as $g(B)K_D(s, n)$ and $g(B)K_C(s, n)$, respectively.

The net harvest revenue is given by $pf(T - A; n)e^{-r(T-A)} - wn - \gamma B$. The forest manager maximizes net harvest revenue by choosing the rotation age (under technologically fixed ditching) and the size of the overland flow field subject to the constraint on the upper limit of the nutrient load. Thus, the economic problem of the landowner over one rotation period is:

$$\text{Max} \quad pf(T - A; n)e^{-r(T-A)} - wn - \gamma B$$

$$\text{s.t.} \quad \bar{z}_p \geq \int_0^x [1 - g(B)]K_D(s, n) + \left\{ \int_0^x [1 - g(B)]K_C(s, n) \right\} e^{-r(T-A)}$$

Recall that the loads from ditch cleaning start immediately, but loading from clear-cutting starts naturally after the cutting; therefore, the latter term is discounted.

The Lagrangian function, L of the problem reads:

$$L = pf(T - A; n)e^{-r(T-A)} - wn - \gamma B + \lambda \left\{ \bar{z}_p - \int_0^x [1 - g(B)]K_D(s, n) - \left[\int_0^x [1 - g(B)]K_C(s, n) \right] e^{-r(T-A)} \right\} \quad (5)$$

The first-order conditions of the maximization problem can be expressed as follows:

$$L_T = pf_T(T - A; n) - rpf(T - A; n) + \lambda \left\{ r \left[\int_0^x [1 - g(B)]K_C(s, n) \right] \right\} = 0 \quad (6)$$

$$L_B = -\gamma + \lambda \left\{ \int_0^x g_B(B)K_D(s, n) + \left[\int_0^x g_B(B)K_C(s, n) \right] e^{-r(T-A)} \right\} = 0 \quad (7)$$

$$L_\lambda = \bar{z}_p - \int_0^x [1 - g(B)]K_D(s, n) - \left[\int_0^x [1 - g(B)]K_C(s, n) \right] e^{-r(T-A)} = 0 \quad (8)$$

From equation (6), the optimal time to clear-cut the stand is affected, in addition to the first conventional terms, by the Lagrangian multiplier and the interest cost term it multiplies. This term tends to postpone the clear-cut and the associated nutrient loading to reduce the cost of establishing the overland flow field. Equation (7) indicates the choice of the overland flow field area depending on the constraints on nutrient flows. The unit cost is constant, but the benefits from nutrient reduction depend via λ on the tightness of the nutrient load constraint—the lower this value, the larger must be the size of the overflow field. Finally, equation (8) simply

³ The analysis starts at the time of ditch cleaning. Thus, if there is any harvesting before ditch cleaning, such as harvesting of trees alongside ditches to enable ditch cleaning with an excavator, it is not considered in our model.

⁴ Chang [38] maximizes the land expectation value with respect to both the rotation age and the planting density. Amacher et al. [39] examines the effects of forest productivity taxes when the landowner chooses the optimal rotation age and initial stand investment.

requires that the constraint on the upper limit of the nutrient load is binding. Note that λ is present in equations (6) and (7). It depends via (6) on the timber price and via (7) on the unit costs of the overflow field, as well as on the ability of the field to reduce nutrients. We cannot solve λ explicitly but use comparative statics to examine its dependences.

The second-order conditions of the problem are given in Appendix A. We assume that direct impacts dominate. Starting comparative statics with the constraint, the upper limit on the loads, we have that $\frac{\partial T}{\partial z_p} < 0$, $\frac{\partial B}{\partial z_p} < 0$ and $\frac{\partial \lambda}{\partial z_p} < 0$. Thus, increasing the upper limit on nutrient loads prepones the optimal time of the clear-cut and decreases the optimal size of the overland flow field. Furthermore, it also decreases the marginal abatement costs of nutrients. For an increase in timber price, we have that $\frac{\partial T}{\partial p} < 0$, $\frac{\partial B}{\partial p} > 0$ and $\frac{\partial \lambda}{\partial p} > 0$. Thus, a higher timber price shortens the optimal time of the clear-cut and increases the size of the overflow field. Naturally, a higher timber price increases the marginal abatement costs. For an increase in the unit cost of the overland flow field, we have that $\frac{\partial T}{\partial \gamma} > 0$, $\frac{\partial B}{\partial \gamma} < 0$ and $\frac{\partial \lambda}{\partial \gamma} > 0$. Thus, an increase in the unit cost of the overland flow field postpones the optimal time of the clear-cut and decreases the optimal size of the overland flow field. As the unit cost of the overland flow field increases, the marginal abatement costs increase. Finally, the effects of the real interest rate on the optimal time of the clear-cut, the size of the overland flow field and the marginal abatement costs are ambiguous.

Thus, the marginal abatement cost of the overflow field can be expressed as.

$MAC = \lambda(\bar{z}_p, \gamma, p, r)$. Again, for a given unit cost of the overland flow field, timber prices and a real interest rate, the MAC-curve increases as the upper limit on the nutrient loads tightens.

3. A numerical application to Finnish forestry and water protection

Based on the theoretical model, we now calculate the numerical marginal abatement costs using buffer zones, overland flow fields, and sedimentation ponds as water protection measures. The actual decision of using buffer zones as a water protection measure in mineral soil forestry is made at the time of clear-cutting of the stand. Thus, we calculate the marginal abatement costs of reducing the nutrient loads using buffer zones at the time of the clear-cut, which takes place at the optimal rotation age. Mathematica was used to calculate the marginal abatement costs.

3.1. Marginal abatement costs of nutrient load reduction in mineral soil forests: buffer zone

In our numerical model, we use the growth of Norway spruce in southern Finland calibrated by Tahvonen and Salo [40]:

$$f(T^*) = \frac{500}{1 + 49e^{(-0.048T^*)}} \quad (9)$$

Equation (9) represents a logistic forest growth as a function of the rotation age and produces the maximum stock by $500 \text{ m}^3 \text{ ha}^{-1}$. The parameters in the denominator determine the rate and concavity of forest growth.

Clear-cuts in mineral soils cause both nitrogen and phosphorus loads to watercourses. The nitrogen load data in the absence of a buffer zone is based on Miettinen et al. [30], and the phosphorus load data is derived from Finér et al. [2]. The loads are assumed to be similar with or without any soil preparation [2]. The phosphorus load is converted to nitrogen equivalents (Ne) using the Redfield ratio, which is the constant ratio of nitrogen and phosphorus mass among marine plankton [41]. Thus, the phosphorus load is multiplied by 7.2 to estimate the phosphorus load as nitrogen equivalents. The nutrient load, $H(s)$, ($\text{kg ha}^{-1} \text{ year}^{-1}$), thus consists of both the nitrogen and phosphorus loads.

The nitrogen retention capacity of the buffer zone was estimated by the FEMMA-model,⁵ which simulates retention when the share of the buffer zone relative to the total clear-cut area changes from zero to 20%. The nitrogen reduction as a share of the loads is a concave function of the size of the buffer zone, m , as follows:

$$g(m) = 0.4962m^{0.3983} \quad (10)$$

As Fig. 1 shows, the share of nitrogen reduction increases with the size of the buffer zone, but in a decreasing fashion. The exponent parameter determines the degree of concavity of the retention, that is, the decreasing marginal productivity of the buffer zone. As there are no estimated reduction functions for phosphorus retention, we use the same reduction function for phosphorus as used for nitrogen.

The timber price is 34 € m^{-3} for stem wood⁶ [43], and the real interest rate used is 2%. The time of the clear-cut is set at 83 years, giving a timber volume of $262 \text{ m}^3 \text{ ha}^{-1}$ for the clear-cutting. The marginal abatement cost and the buffer zone size are calculated for consecutively tightening levels of the upper limit on the nutrient load.

The results are collected in Table 1. The first two columns indicate the reduction targets based on the tightening levels of the upper limits on the nutrient load, the third column gives the size of the buffer zone and the next two provide the marginal and total costs of abatement. The marginal abatement costs of nutrients (Ne) are high and increase strongly with the reduction target. The reason for this effect is that leaving mature trees standing is very costly and the nutrient reductions per hectare are low. The last two columns provide

⁵ A more detailed description of the ecohydrologic model is found in Miettinen et al. [30].

⁶ The timber price estimate is based on timber price statistics from the year 2016 for spruce saw logs and pulpwood. The estimate is calculated as a weighted average according to the share of spruce saw logs and pulpwood measured in the National Forest Inventory (VMI11) for Finland [42].

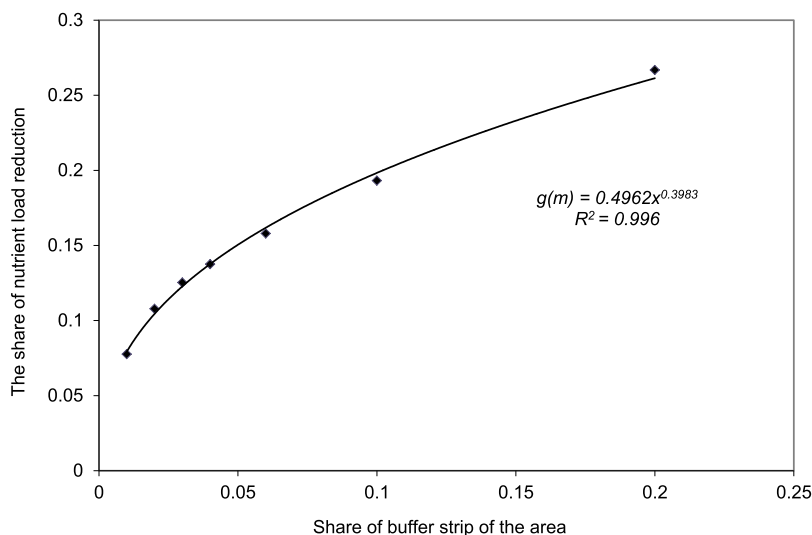


Fig. 1. Share of the nutrient load retention as a function of the size of the buffer zone.

a generalization to the annual clear-cut area in Finland, which was 141 044 ha in 2016 [43]. We use the estimate of the shoreline length per forest area, 11 m ha^{-1} [23], to estimate the total costs, assuming that buffer zones are applied to all clear-cut areas with shorelines (15 515 ha) under the nutrient reduction target. The resulting reductions in loads would be relatively small, but the costs would be very high.⁷

Fig. 2 illustrates the marginal abatement cost function, which is increasing and convex in abatement. The marginal abatement cost function (using the buffer zone, BZ, as a water protection measure) as a function of the nutrient abatement, a , is given by:

$$MAC_{BZ} = 236.77a^2 + 371.79a \quad (11)$$

We provide a sensitivity analysis with respect to timber prices in Appendix B in Table B.1. The timber prices are changed to 25% below and above the basic run estimate.

3.2. Marginal abatement costs of nutrients and sediment in drained peatland forests: overland flow field and sedimentation pond

We next determine the marginal abatement costs of nutrients using overland flow fields as a water protection measure in peatland forestry. As an additional result, we also calculate the marginal abatement costs of sediments using either an overland flow field or a sedimentation pond (the analytical derivation of the abatement cost function is given in Appendix A). Sedimentation ponds are excavated in the main outlet ditch of the drainage area to slow down the flow of water and enable sedimentation [6].

We postulate a catchment area of 50 ha, out of which 30% (15 ha) is subjected to ditch cleaning after the first commercial thinning of the stand. At the end of the rotation period, the same area is assumed to be clear-cut. The average stumpage prices from regeneration felling (Northern Ostrobothnia area in central-western Finland) are 52.43 € m^{-3} for saw logs and 18.10 € m^{-3} for pulpwood [43]. These prices differ from those used above for mineral soils because they are regional and relevant to peatland forestry. Ditch cleaning costs are 196 € ha^{-1} [43],⁸ and the real interest rate is 2%. The costs of the overland flow field are 750 € ha^{-1} [46], and the costs of the sedimentation pond 1 € m^{-1} (Seppäkoski 2016, personal communication, 29 January).

Forest growth in peatlands is estimated using the Motti stand simulator, which predicts growth and mortality of the trees and the effects of silvicultural treatments on tree growth at the stand level under Finnish conditions (Motti-software 3.2 <http://www.metla.fi/metinfo/motti/index-en.htm>, last accessed February 2017, see Refs. [47,48]). For drained peatlands, Motti predicts both the need for ditch network maintenance and the respective growth response [49–51].

⁷ As the calculation is based on the average value of the shoreline length per forest land area, the fact that the costs of buffer zones differ between locations is not included in the estimates of the total costs.

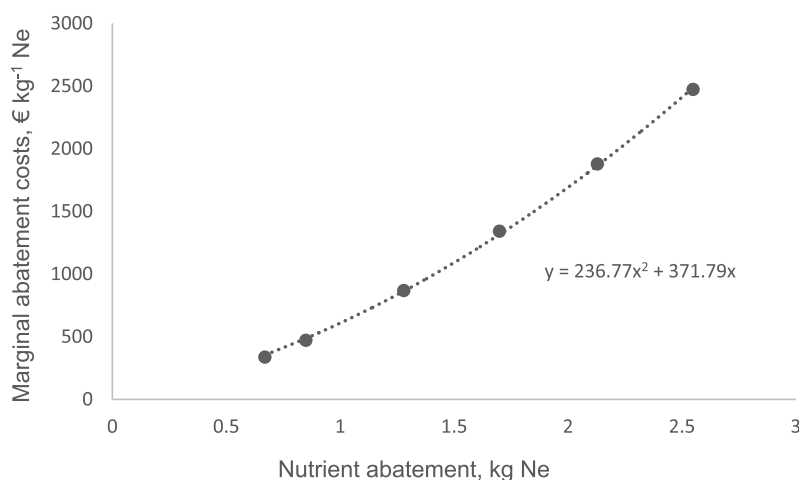
⁸ Water protection costs are excluded. The cost estimate is based on statistics from the year 2014, converted to the 2016 price level [44].

⁹ The estimated costs of the overland flow field are based on the project “Cost-effective water protection measures” by Tapio Ltd. To this estimate, we also added the value of lost land area using the bare land value of 115 € ha^{-1} . Overland flow fields are established on peatlands, but corresponding bare land value estimates were not available. Thus, the value here is calculated based on the estimate for low-productivity mineral soil forests in the Northern Ostrobothnia area in central-western Finland [45]. The final estimate of the cost of the overland flow field was converted to 2016 prices [44].

Table 1

Marginal abatement costs of nutrients (€ kg⁻¹ Ne): buffer zone. Nutrient reduction (% Ne), nutrient reduction (kg ha⁻¹ Ne), the size of the buffer zone (% of the total area), marginal abatement costs of nutrients (€ kg⁻¹ Ne), total costs per hectare (€ ha⁻¹), total nutrient reduction (Ne, tonnes/year/ha shoreline), and total costs (M €/year/ha shoreline).

Buffer zone						
Nutrient reduction, % Ne	Nutrient reduction, kg ha ⁻¹ Ne	The size of the buffer zone, %	Marginal abatement costs, € kg ⁻¹ Ne	Total cost, € ha ⁻¹	Nutrient reduction, Ne, tonnes/ha shoreline	Total costs, M €/ha shoreline
8	0.67	1	336	107	10	2
10	0.85	2	470	183	13	3
15	1.28	5	867	470	20	7
20	1.70	10	1340	925	26	14
25	2.13	18	1877	1606	33	25
30	2.55	28	2472	2517	40	39

**Fig. 2.** The marginal abatement costs of nutrients: buffer zone.

We derive the forest growth functions using Motti simulations and assuming ditch cleaning. The stand (growing on the Ptkg I drained peatland site type according to Laine and Vasander [52],¹⁰) is assumed to be dominated by Scots pine and located in the commune of Liminka, Northern Ostrobothnia area in central-western Finland, where the average temperature sum is 1045.2 d.d. At the beginning of the simulation, the stand age was 20 years (based on the drainage age, i.e., the time elapsed since the initial drainage¹¹), the average stand basal area was 17.4 m² ha⁻¹, the stem number was 2332 stems ha⁻¹, the basal area weighted mean diameter was 12.4 cm, the dominant height was 11.4 m and the volume was 88.9 m³ ha⁻¹. Thinning, ditch cleaning and clear-cutting followed the Finnish silvicultural recommendations [53].

The nitrogen and phosphorus loads from the clear-cut areas in drained peatlands and the sediment loads due to ditch cleaning are based on the average loads in Finland [2]. We assume that clear-cuts in drained peatland forests follow the best management practices (harvesting during the frozen-soil period in winter and using harvest residues as mats against heavy harvesting machinery) and only increase the dissolved nutrient exports. In contrast to clear-cuts, ditch cleaning has a minor impact on dissolved nutrient exports [54]. Nitrogen and phosphorus loads from ditch cleaning are thus bound to the sediment loads. The amount of nitrogen is estimated to be 0.666% of the sediment load and that of phosphorus is 0.1%. The estimate for nitrogen is based on the average sediment nitrogen content in Nieminen et al. [3], and the estimate for phosphorus is derived from Finér et al. [2].

We employ the MATLAB curve fitting-tool to estimate the retention functions. First, we describe how the overland flow field retains

¹⁰ Drained peatland site types according to the Finnish nomenclature [52]: Ptkg = *Vaccinium vitis-idaea* type.

¹¹ The stands in the Ptkg I site are not even-aged in practise, as there are trees born both before and after the first drainage. When estimating the stand growth in peatlands, Motti simulator does not use the age of the trees to predict the tree growth.

nitrogen, phosphorus and sediment from clear-cuts and ditch cleaning in peatlands. We assume that an overland flow field reduces only 30% of the dissolved nitrogen load caused by clear-cutting in peatlands, because approximately 70% of the nitrogen load from peatland clear-cuts is in the form of dissolved organic nitrogen [55], and overland flow fields retain only inorganic nutrients [56]. Drawing on Hynninen et al. [15],¹² in Fig. 3, the share of inorganic nitrogen load reduction, $g(B_{FN})$, as a function of the size of the overland flow field, B_{FN} (subscript F refers to the overland flow field and N to nitrogen), is fitted to:

$$g(B_{FN}) = -1.791B_{FN}^{-0.0656} + 3.158 \quad (12)$$

There is no data to estimate the retention function of phosphorus loads from clear-cuts. We assume that clear-cuts only increase dissolved nutrients and that overland flow fields retain only inorganic forms of dissolved nutrients [56]. According to Nieminen [57], approximately 77% of the dissolved phosphorus load from clear-cuts in peatland forests is in inorganic form. Drawing on the average retention of dissolved inorganic phosphorus in Väänänen et al. [13] and Silvan et al. [58], we assume that overland flow fields are able to retain 77% of this load.

Furthermore, a nonlinear regression of the sediment load reduction as a function of the size of the overland flow field is based on the data by Nieminen et al. [12] and Sallantausta et al. [59]. Eight overland flow fields were included in the analysis, and the overland flow field sizes varied from 0.05% to 4.88% of the catchment areas. From Fig. 4, we can see that the share of the sediment load reduction, $g(B_{FS})$, as a function of the size of the overland flow field, B_{FS} (subscript F refers to overland flow field and S to sediment), is given by:

$$g(B_{FS}) = -0.02437B_{FS}^{-0.4997} + 1.016 \quad (13)$$

The overland flow field is assumed to retain sediment-bound nitrogen and phosphorus similarly as sediment, according to the retention function in equation (13).

The retention capacity of a sediment pond is based on Nieminen et al. [60].¹³ The maximum efficiency of sedimentation ponds is approximately 55% of the sediment load. Further increasing the pond volume after reaching this level has very little effect on the retention. As Fig. 5 shows, the share of the sediment load reduction, $g(B_{PS})$, as a function of the pond volume, B_{PS} (subscript P refers to sedimentation pond and S to sediment), is:

$$g(B_{PS}) = 0.03089B_{PS}^{0.4625} \quad (14)$$

3.2.1. Marginal abatement costs of nutrients: overland flow fields

We include both the nitrogen and phosphorus loads from peatland clear-cuts and ditch cleaning and calculate the marginal abatement costs of nutrients when the phosphorus load is included as nitrogen equivalents (Ne). Table 2 suggests that the marginal abatement costs of nutrients are 0.02 € kg⁻¹ Ne when the reduction target is set to 8% and the interest rate is 2%. The marginal abatement costs increase to 0.04 € kg⁻¹ Ne when the reduction target is set as high as 30%. A comparison to marginal abatement costs in mineral soil forestry and agriculture shows that overland flow fields in peatland forestry clearly have the lowest marginal abatement costs of nutrients.

Fig. 6 shows that the marginal abatement costs of using overland flow fields are surprisingly low, albeit increasing with abatement. The marginal abatement cost function of using an overland flow field, F , as a water protection measure as a function of abatement, a , is given by:

$$MAC_F = 0.00011a^2 - 0.000016a + 0.01443 \quad (15)$$

3.2.2. Marginal abatement costs of sediment: overland flow field and sedimentation pond

Forestry in Finland is an exceptionally high source of sediments due to forest drainage in peatlands. Therefore, we also define the marginal abatement cost of sediment reduction (for the analytical derivation of the abatement cost function, see Appendix A). We estimate the marginal abatement costs of sediment for both overland flow fields and sedimentation ponds, as both are used to decrease sediment transport in peatland forestry. Sediment loads are assumed to be caused only by ditch cleaning, and the loads are based on the average loads in Finland [2]. However, here, we double these loads, because it is not realistic to assess the efficiency of sediment ponds with average loads. This is because they are efficient in reducing sediment loads only from larger-than-average input loads, at about >10 000 kg ha⁻¹ year⁻¹ [60].

For overland flow fields, Table 3 shows that the marginal abatement costs of sediment are 0.002 € kg⁻¹ when the reduction target is set to 20% and the interest rate is 2%. The marginal abatement costs increase to 0.011 € kg⁻¹ when the reduction target is set as 55%. For using a sedimentation pond as a water protection measure in conjunction with ditch cleaning, the marginal abatement costs of

¹² In Hynninen et al. [15], the sizes of the overland flow fields varied between 0.09% and 4.88% of the catchment areas. The retention function is estimated using the data, where the amount of ammonium entering the overland flow field is at least 5 kg/year. Even though the data in Hynninen et al. [15] is only for ammonium, the function (12) is applied for both ammonium and nitrate. Vikman et al. [14] reported similar nitrate and ammonium retentions by overland flow fields and showed that their retentions were similarly affected by overland flow field and catchment characteristics.

¹³ The original data consisted of 37 sedimentation ponds, of which 17 were excavated on erosion-sensitive soils and increased rather than decreased the suspended solids concentrations. The excavation of such ponds is no longer recommended. The retention function in equation (14) is estimated using data from 12 sedimentation ponds which clearly decreased the sediment load and received a sediment loading of >10 000 kg year⁻¹ [60]. With lower input loadings, sedimentation ponds had negligible retention capacity.

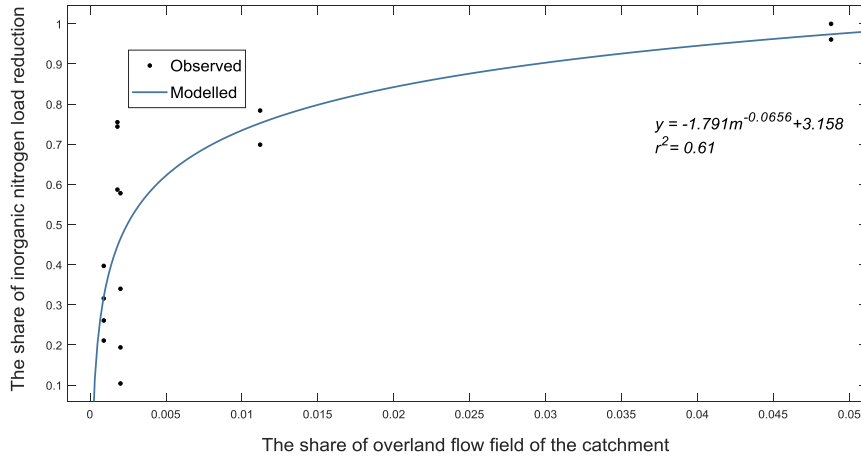


Fig. 3. Share of the inorganic nitrogen retention as a function of the size of the overland flow field.

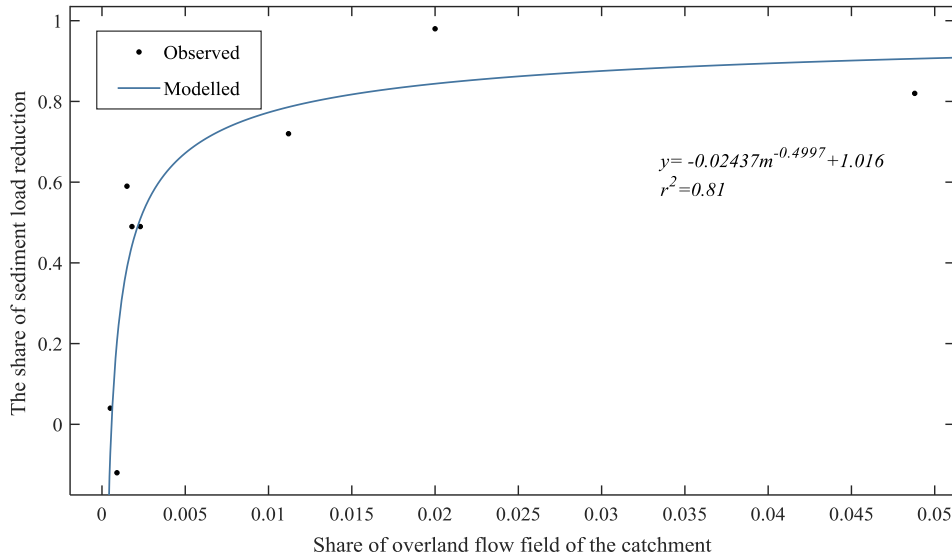


Fig. 4. The share of the sediment load reduction as a function of the size of the overland flow field.

sediment are 0.015 € kg⁻¹ when the sediment reduction is set to 20%. They increase to 0.048 € kg⁻¹ when the target level for sediment reduction is increased to 55%. Thus, the marginal abatement costs of sediment retention are significantly lower for overland flow fields than for sedimentation ponds.

Fig. 7 provides a graphical illustration of the marginal abatement costs of overland flow fields and sedimentation bonds. The marginal abatement costs are rather small for both. When the sediment abatement increases, the difference between the marginal abatement costs increases. The marginal abatement cost functions (using an overland flow field, F , and a sedimentation pond, P , as water protection measures) as a function of sediment abatement, u , are:

$$MAC_F = 4.0 \cdot 10^{-11} u^2 - 6.6 \cdot 10^{-7} u + 0.005 \quad (16)$$

$$MAC_P = 1.4 \cdot 10^{-11} u^2 + 1.8 \cdot 10^{-6} u - 0.001 \quad (17)$$

Table B.2 in Appendix B presents the sensitivity analysis and shows that an overland flow field also provides lower marginal costs when the establishment costs are increased or decreased by 25%.

We have now derived the marginal abatement costs of nutrients and sediments for forestry. We next put the defined marginal abatement costs of nutrients into action and examine how a cost-effective water protection policy in a river basin would look. Buffer strips and restrictions on nitrogen fertilization in agriculture as water protection measures are included in the model. For forestry, we include the use of buffer zones in mineral soils and overland flow fields in peatlands in the analysis.

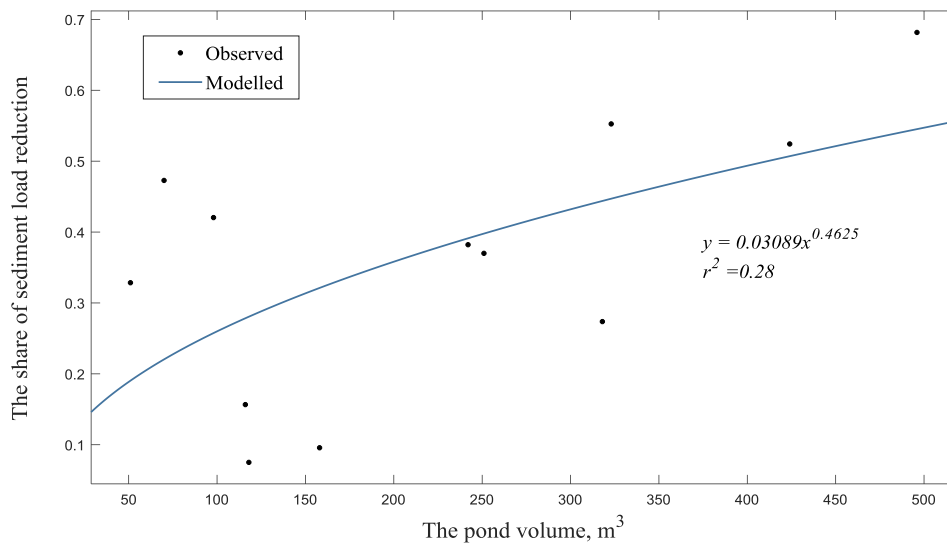


Fig. 5. The share of the sediment load reduction as a function of the pond volume.

Table 2

Marginal abatement costs of nutrients (€ kg⁻¹ Ne): overland flow field. Nutrient reduction (% Ne), nutrient reduction (Ne kg ha⁻¹), the size of the overland flow field (% of the total catchment area), marginal abatement costs (€ kg⁻¹ Ne) and total costs (€ ha⁻¹).

Overland flow field				
Ne reduction, %	Ne reduction, kg ha ⁻¹	The size of the overland flow field, %	Marginal abatement costs, € kg ⁻¹ Ne	Total costs, € ha ⁻¹
8	3.98	0.01	0.02	0.06
10	4.97	0.01	0.02	0.08
15	7.46	0.02	0.02	0.12
20	9.95	0.02	0.03	0.18
25	12.43	0.02	0.03	0.25
30	14.92	0.02	0.04	0.34

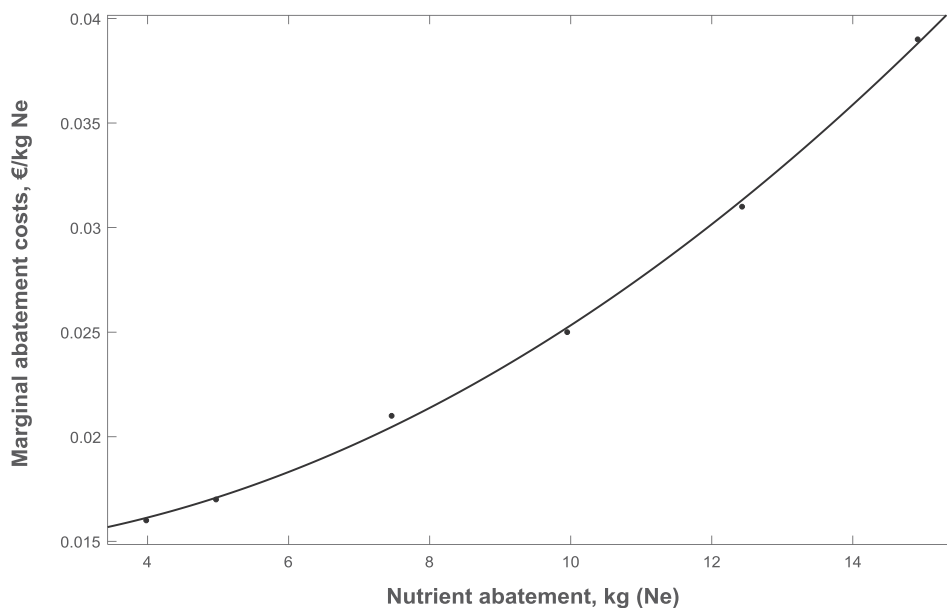
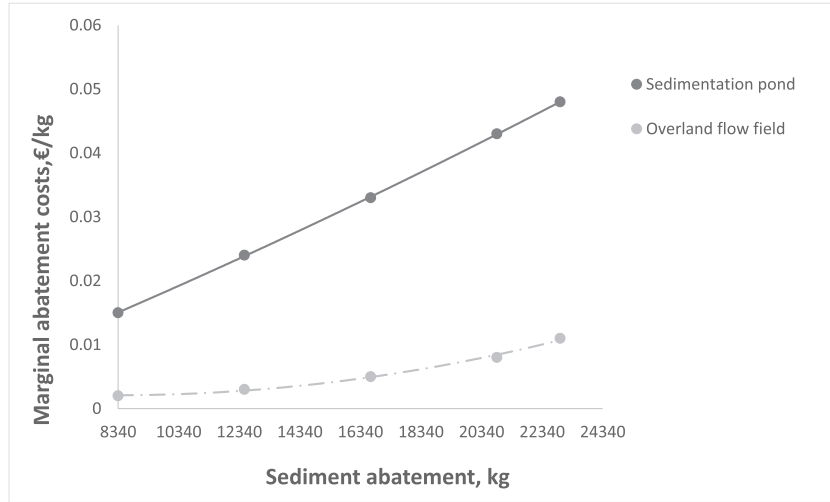


Fig. 6. The marginal abatement costs of nutrients: overland flow field. The interest rate is 2%.

Table 3Marginal abatement costs (€ kg⁻¹) of sediment: overland flow field and sedimentation pond.

Sediment reduction, %	Overland flow field		Sedimentation pond	
	The size of the overland flow field, %	Marginal abatement costs, € kg ⁻¹	Pond volume, m ³	Marginal abatement costs, € kg ⁻¹
20	0.09	0.002	57	0.015
30	0.12	0.003	136	0.024
40	0.16	0.005	254	0.033
50	0.22	0.008	412	0.043
55	0.27	0.011	506	0.048

**Fig. 7.** Marginal abatement costs: overland flow field and sedimentation pond. The interest rate is 2%.

4. The river basin model

We consider a river running into the Baltic Sea, where agriculture and forestry are sources of nutrient loads through the river to the sea. For modeling, we choose the River Temmesjoki located in Northern Ostrobothnia and running into the Bothnian Sea, a subregion of the Baltic Sea. The water quality in the Bothnian Sea is better than that in many other subregions of the Baltic Sea, but nevertheless, it suffers from eutrophication caused by excess nutrient loads. We first sketch the cost-effectiveness conditions of the river basin model and then apply the marginal abatement curves in forestry and those in agriculture.

4.1. The cost-effectiveness conditions

Let the length of the river from its mouth to the head be T . The distance of each location from the river head is denoted by i , $i = 1, \dots, 7$. Nitrogen and phosphorus loads from agriculture and forestry degrade in the stream before entering the sea according to the average degradation rate δ_i . This rate indicates the share of nutrient loads from the source entering the sea, depending on location i ; thus, $0 \leq \delta_i \leq 1$. The water quality is monitored at the river mouth. The nitrogen equivalent load (Ne) to the sea before abatement is e_{ij} , and abatement at the source is denoted by a_{ij} , where $j = 1, 2, 3$ defines agricultural land, mineral soil forests and peatland forests, respectively. Thus, the nutrient load at the river mouth, z_r (r refers to the loads at the river mouth), is:

$$z_r = \sum_{i=1}^7 \sum_{j=1}^3 \delta_i (e_{ij} - a_{ij}) \quad (18)$$

Let \bar{z}_r denote the upper limit on the nutrient load into the Baltic Sea and the total abatement costs be $c_{ij}(a_{ij})$. Then, the economic problem of the social planner is to minimize the sum of the total abatement costs subject to the imposed upper limit on the nutrient loads. The Lagrangian function for the constrained minimization problem is:

$$L = \sum_{i=1}^7 \sum_{j=1}^3 c_{ij}(a_{ij}) + \mu \left[\sum_{i=1}^7 \sum_{j=1}^3 \delta_i (e_{ij} - a_{ij}) - \bar{z}_r \right] \quad (19)$$

The first order conditions are as follows:

$$L_{aj} = c'_{ij}(a_{ij}) - \mu\delta_i = 0 \quad (20)$$

$$L_\mu = \sum_{i=1}^7 \sum_{j=1}^3 \delta_i (e_{ij} - a_{ij}) - \bar{z}_r = 0 \quad (21)$$

The shadow price associated with the constraint is μ . The marginal abatement cost is $c'_{ij}(a_{ij})$. From equation (20), for any two sources, $j = 1, 2$, the cost-effective solution requires that:

$$\frac{c'_{i1}(a_{i1})}{\delta_i} = \frac{c'_{i2}(a_{i2})}{\delta_i} = \mu \quad (22)$$

This condition simply requires that the marginal abatement costs weighted by the share with which each source pollutes the sea should be equal between polluters. In other words, the marginal costs from reducing pollution at the river mouth must be equal.

4.2. A numerical application to the River Temmesjoki

The length of the River Temmesjoki is 73 km, and the catchment size is 1145 km². Open GIS-data from the Finnish Environment Institute [61], Natural Resources Institute Finland [62] and National Land Survey of Finland [63] was used to divide the river into 7 locations (10 km each along the river) and estimate the areas of agriculture and forestry (separately for mineral soils and peatlands) in each location. Unlike in agriculture, management measures are not conducted every year in forestry. We thus needed to estimate the areas of annual clear-cuts in mineral soils and the annual ditch cleaning operations and clear-cuts in peatlands. The different management cycles in agriculture (annual management measures) and forestry (infrequent measures) imply that agricultural land provides a significantly larger area for water protection annually than does forest land, at approximately 16 438 ha (agriculture) versus 255 ha (forestry)¹⁴ in the River Temmesjoki.

Previous literature on cost-effectiveness in water protection also covers different sectors. The marginal costs of reducing nitrogen and phosphorus in agriculture, water treatment plants, atmospheric deposits and wetlands were quantified by Gren et al. [64], Turner et al. [65], Helin et al. [66], Lankoski and Ollikainen [17], Hautakangas et al. [16], Helin [18] and Lötjönen and Ollikainen [20]. Iho [67] studied the cost-effectiveness of water protection measures to reduce the phosphorus load in agriculture. Nitrogen abatement in agriculture is included in the studies by Laukkanen and Nauges [19,68]. In the Baltic Sea scale, Gren et al. [69], Elofsson [70], Gren and Elofsson [71] and Wulff et al. [72] estimated the minimum cost solutions and cost-effectiveness for reaching specified nutrient reduction targets, and Hautakangas and Ollikainen [73] studied nutrient trading between wastewater treatment plants.

We develop the marginal abatement costs of nutrients in agriculture using data from Lötjönen and Ollikainen [74],¹⁵ except that we convert the prices and costs to the 2016 price level [44]. The phosphorus load is, again, converted to nitrogen equivalents (Ne). The marginal abatement costs of nutrients in agriculture are presented in Fig. 8. It shows that the marginal abatement costs of nutrients increase with the load reduction target but strongly only after the target implies a 20% reduction, where the nutrient reduction (Ne) is over 5 kg/ha. The choices of buffer strips and fertilizer input as well as costs are reported in more detail in Appendix C in Table C.1. The marginal abatement cost function (for agriculture A) as a function of the nutrient abatement, a , is given by:

$$MAC_A = 0.1018a^2 - 0.0457a \quad (22a)$$

We next assume that overland flow fields can be used as a water protection measure for 50% of the ditch cleaning and clear-cut areas in the drained peatlands. For many reasons, it is often unfeasible to construct an overland flow field downstream from a peatland drainage area [3]. We use an estimate of 0.003 as the rate of nutrient degradation along the river [34]. The cost-effective solution is solved subject to the nutrient reduction target at the river mouth, which is set either to 10% or 30% from the baseline condition (with no water protection). The model was solved with Excel Solver. The levels of marginal abatement costs, μ , when the nutrient reduction target is set to 10% and 30% are 0.53 € kg⁻¹ and 5.67 € kg⁻¹, respectively.

We report the key results in Table 4, including locations, source-based loads, total loads, and reductions under the targeted reduction rates. The highest nutrient reductions in the cost-effective solution are in agriculture. Given that the marginal abatement costs of nutrients using buffer zones in mineral soil forests are high (Table 1), their role is minor in the cost-effective solution. If the nutrient reduction target is set as 10%, the overall nutrient reduction in the catchment is 39 690 kg Ne, with agriculture accounting for approximately 38 643 kg Ne (97%) and forestry 1047 kg Ne (3%). If the target rises to 30%, the total nutrient reduction increases to 119 070 kg Ne, of which agriculture accounts for 118 010 kg Ne (99%) and forestry 1060 kg Ne (1%).

Table 5 shows the costs of nutrient reductions and the sizes of the different water protection measures when the target level varies from 10% to 30%. With the 10% reduction target, the size of the buffer strips in agriculture varies from 0.04% to 0.07% of the land area. The nitrogen fertilizer application rate in agriculture varies only slightly (from 120.6 kg ha⁻¹ to 121.2 kg ha⁻¹). In forestry on

¹⁴ Our GIS analysis showed that the forest area in the River Temmesjoki catchment was 80 835 ha, and the share of mineral soil forests was 45% of the forest area. Based on these estimates and statistics on clear-cut areas and forest land areas in Northern Ostrobothnia from the year 2016, we estimated that 0.52% of the mineral soils are clear-cut annually in the River Temmesjoki catchment. Similarly, based on statistics on ditch cleaning and peatland areas in Northern Ostrobothnia, ditch cleaning is estimated to be conducted on 0.2% of the peatlands [43], and here, we assume that the same area is clear-cut at the end of the rotation period.

¹⁵ Data from Lötjönen and Ollikainen [74] is presented in Appendix C.

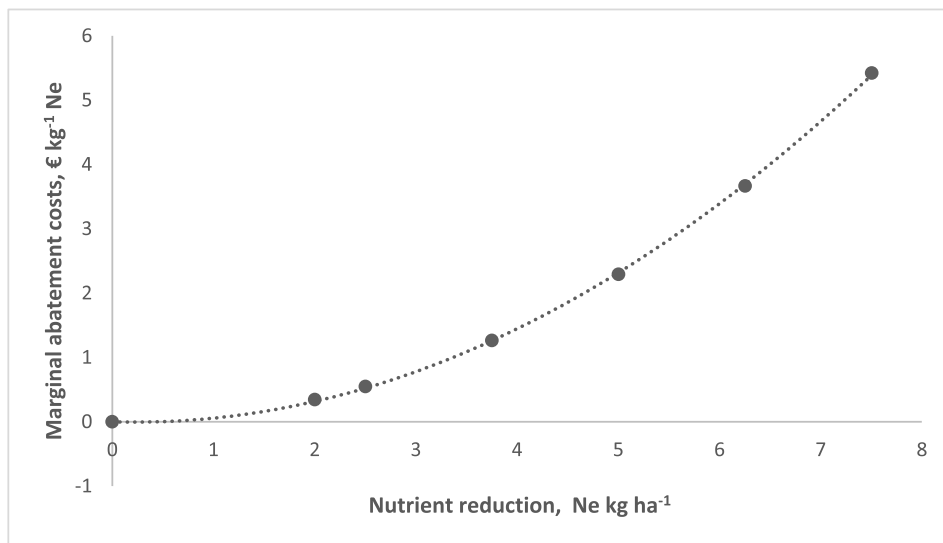


Fig. 8. The marginal abatement costs of nutrients: agriculture.

Table 4

The nutrient (nitrogen equivalents, Ne) reductions per hectare (kg ha^{-1}) of total agricultural area, clear-cut mineral soil forest area (Forestry, mineral soil), and ditch maintenance-treated and clear-cut peatland forest area (Forestry, peatland) and the total nutrient reductions (kg Ne) in the cost-effective solution as the target level for nutrient retention varies from 10% to 30% in the Temmesjoki River. The water protection measures used are buffer strips and restrictions on nitrogen fertilizer (agriculture), buffer zones (mineral soil forests) and overland flow fields (peatland forests). The length of the river is 70 km. The impact of the degradation rate is included in all figures.

Location (average distance to river mouth, km)	Sector	Total area, ha	Baseline		Cost-effective solution			
			Ne export, kg ha ⁻¹	Ne export, kg	Nutrient reduction target			
					10%	30%	10%	30%
					Ne reduction, kg ha ⁻¹		Ne reduction, kg	
i = 1(5)	Agriculture	3882	24.65	95 669	2.50	7.64	9551.46	29 217.31
	Forestry, mineral soil	15	8.38	123	0.00	0.02	0.02	0.22
	Forestry, peatland	3	48.99	152	29.80	29.82	45.59	45.62
i = 2(15)	Agriculture	10651	23.92	254 746	2.46	7.52	25 091.80	76 599.48
	Forestry, mineral soil	45	8.14	366	0.00	0.01	0.07	0.51
	Forestry, peatland	13	47.54	609	34.85	35.10	213.34	214.85
i = 3(25)	Agriculture	806	23.21	18 708	2.43	7.43	1818.06	5554.87
	Forestry, mineral soil	53	7.90	420	0.00	0.01	0.07	0.65
	Forestry, peatland	15	46.14	687	36.47	36.75	251.99	253.95
i = 4(35)	Agriculture	296	22.53	6672	2.40	7.32	640.91	1951.88
	Forestry, mineral soil	33	7.66	253	0.00	0.02	0.05	0.49
	Forestry, peatland	14	44.77	607	33.78	34.61	206.15	211.22
i = 5(45)	Agriculture	46	21.86	1007	2.38	7.33	96.00	295.08
	Forestry, mineral soil	23	7.44	173	0.00	0.01	0.03	0.27
	Forestry, peatland	10	43.45	436	34.09	34.93	149.58	153.29
i = 6(55)	Agriculture	20	21.21	433	2.72	6.69	47.18	115.82
	Forestry, mineral soil	15	7.22	111	0.00	0.01	0.02	0.17
	Forestry, peatland	9	42.17	381	33.21	33.37	127.11	127.70
i = 7(65)	Agriculture	737	20.59	15 176	2.30	7.05	1397.74	4275.08
	Forestry, mineral soil	4	7.00	26	0.00	0.00	0.00	0.01
	Forestry, peatland	4	40.92	145	36.17	35.28	52.84	51.54
Total		16 693		396900			39 689.99	119 069.98

Table 5

The costs per hectare (€ ha⁻¹) of total agricultural area, clear-cut mineral soil forest area (Forestry, mineral soil), and ditch-maintenance-treated and clear-cut peatland forest area (Forestry, peatland) and the total costs (€) and optimization of water protection measures in the cost-effective solution as the target level varies from 10% to 30%. BS, % = agriculture, buffer strip; N, kg ha⁻¹ = agriculture, N fertilizer; BZ, % = forestry, buffer zone in mineral soils; overland flow field, % = forestry, overland flow field in peatlands. The nitrogen fertilizer application rate in agriculture is 122 kg/ha in the private optimum without any restriction regarding the water protection.

Location (average distance to river mouth, km)	Sector	Total area, ha	Cost-effective solution											
			Nutrient (Ne) reduction target											
			10%		30%		10%		30%		10%		30%	
			Costs, € ha ⁻¹		Total costs, €		BS, %		N, kg ha ⁻¹		BZ, %		Overland flow field, %	
i = 1(5)	Agriculture	3882	0.39	13.80	1499.41	53 578.76	0.06	121.0					1.59	110.2
	Forestry, mineral soil	15	0.00	0.04	0.01	0.64					0.00			0.00
	Forestry, peatland	3	1.40	1.40	2.17	2.17						0.08		0.08
i = 2(15)	Agriculture	10651	0.37	13.15	3930.69	140 101.56	0.05	121.0					1.52	110.5
	Forestry, mineral soil	45	0.00	0.03	0.02	1.16					0.00			0.00
	Forestry, peatland	13	2.05	2.09	13.14	13.38						0.16		0.17
i = 3(25)	Agriculture	806	0.35	12.65	284.24	10 196.48	0.05	121.1					1.46	110.7
	Forestry, mineral soil	53	0.00	0.03	0.02	1.74					0.00			0.00
	Forestry, peatland	15	2.30	2.35	17.15	17.49						0.21		0.22
i = 4(35)	Agriculture	296	0.34	12.08	100.42	3578.27	0.05	121.1					1.39	111.0
	Forestry, mineral soil	33	0.00	0.05	0.01	1.65					0.00			0.00
	Forestry, peatland	14	1.90	2.02	12.87	13.67						0.14		0.15
i = 5(45)	Agriculture	46	0.33	12.14	15.22	559.29	0.05	121.1					1.40	110.9
	Forestry, mineral soil	23	0.00	0.03	0.01	0.75					0.00			0.00
	Forestry, peatland	10	1.94	2.06	9.75	10.37						0.14		0.16
i = 6(55)	Agriculture	20	0.52	9.12	10.54	186.35	0.07	120.6					1.05	112.5
	Forestry, mineral soil	15	0.00	0.03	0.00	0.48					0.00			0.00
	Forestry, peatland	9	1.82	1.84	8.21	8.31						0.13		0.13
i = 7(65)	Agriculture	737	0.29	10.74	216.61	7920.20	0.04	121.2					1.24	111.6
	Forestry, mineral soil	4	0.00	0.00	0.00	0.00					0.00			0.00
	Forestry, peatland	4	2.25	2.12	4.00	3.76						0.20		0.17
Total		16 693			6124.49	216 196.48								

mineral soils, no buffer zones are used due to their high abatement costs. In peatland forestry, the size of the overland flow field varies from 0.08% to 0.21% of the total peatland catchment area. Under the 30% reduction target, the size of the buffer strip in agriculture is between 1.05% and 1.59% of the land area. The nitrogen fertilizer level varies from 110.2 kg ha⁻¹ to 112.5 kg ha⁻¹. Despite increased targets, no buffer zones are used in mineral soil forests. The size of the overland flow field varies from 0.08% to 0.22% of the total catchment area. These results are as expected, as the marginal abatement cost of nutrients for overland flow fields are the lowest and the marginal abatement costs of nutrients for buffer zones in mineral soil forestry are the highest out of these three water protection measures. At the same time, agricultural land provides a much larger area for water protection than do forest areas.

When the nutrient reduction target is set at 10%, the total cost of nutrient reduction is 6124 €. The share of agriculture is 6057 € (99%) and that of forestry is 67 € (1%), with forestry sector portion consisting almost entirely of costs in peatland forests. When the nutrient reduction target is set higher at 30%, the total cost of nutrient reductions increases to 216 196 €. The share of agriculture is 216 121 € (99.97%), and that of forestry is 76 € (0.03%).

5. Discussion and conclusions

We examined the analytical features of the marginal abatement cost functions of three water protection measures: buffer zones in mineral soil forests and overland flow fields and sedimentation ponds in peatland forestry. We used Finnish data to numerically estimate the marginal abatement costs of these measures for nutrient and sediment reductions. The marginal abatement costs of nutrients were put into action in a river basin model designed for analysis of the cost-effective abatement solution, with agriculture and forestry as polluting sectors.

To our knowledge, this is the first study on the marginal abatement costs of nutrients and sediment using different water protection measures in peatland and mineral soil forests. Interestingly, our study is timely, as recent results suggest that forestry may be a significantly higher source of nutrients and sediments to watercourses than previously estimated, particularly in peatland-dominated regions, such as Finland [4,37,75]. Our results show that there is a need for abatement actions in forestry, even though agriculture carries the main share of abatement efforts.

Our main findings concerning the nutrient abatement costs can be condensed as follows. Buffer zones in mineral soils are very expensive measures, with the marginal costs of nutrients ranging from 470 € kg⁻¹ Ne to 2472 € kg⁻¹ Ne when the nutrient reduction target is 10% and 30%, respectively. In contrast, the marginal abatement costs of nutrients using overland flow fields in peatlands are rather low, ranging from 0.02 € kg⁻¹ Ne at the 10% level to 0.04 € kg⁻¹ Ne when abatement is 30% and the interest rate is 2%.

How do these costs compare with costs in agriculture or in point sources? Finnish studies on the marginal abatement costs of nitrogen in the agricultural sector are summarized by Ollikainen et al. [76]. The marginal abatement costs of nitrogen in agriculture in the study by Lankoski and Ollikainen [17] varied from 4.4 to 15.2 € kg⁻¹ N when the nitrogen reduction target was increased from 10% to 30%. In the case of wastewater treatment plants (Hautakangas et al. [16]), the marginal abatement costs of nitrogen varied between 7.6 and 11.7 € kg⁻¹ N when the nitrogen reduction target was similarly increased between 10 and 30% from the baseline level (with a 4% real interest rate). Additionally, in studies by Helin et al. [66] and Helin [18] the marginal abatement costs of nitrogen in agriculture range from 7.0 to 24.8 € kg⁻¹ N. Thus, our results indicate that the marginal abatement costs of nutrients in mineral soil forests using buffer zones are considerably higher than those in agriculture and wastewater treatment plants. In contrast, the marginal abatement costs of nutrients using overland flow fields in peatland forestry are much lower than those in agriculture and wastewater treatment plants.

Lauren et al. [21] calculated estimates of the unit costs of nitrogen reduction with different intensities of harvesting in the buffer zone area and found that the unit costs of nitrogen reduction were between 219 and 1578 € kg⁻¹ N. Without any harvesting in the buffer zone area, the unit costs of nitrogen reduction were between 634 and 1578 € kg⁻¹ N. Although Lauren et al. [21] estimated the unit costs of nitrogen reduction, rather than the marginal abatement costs, this study confirms our finding that reducing nutrient exports in mineral soil forests using buffer zones is significantly more expensive than reducing nutrient exports in other polluting sectors.

The numerical results also showed that the marginal abatement costs of sediment reduction are significantly higher when using sedimentation ponds compared to overland flow fields as a water protection measure in conjunction with ditch cleaning in peatland forests. We thus recommend the use of overland flow fields as the water protection measure in ditch cleaning instead of sedimentation ponds. However, a major limitation in their use is that creating an overland flow field by restoring a small section of drained peatland area results in the water table rising not only in the overland flow itself but also in the upstream area, potentially decreasing tree growth there.

The river basin model showed that when the four water protection measures (buffer strips and restrictions on nitrogen fertilizer in agriculture, buffer zones in mineral soil forests, and overland flow fields in drained peatlands) are included in the same cost-effective framework, the highest nutrient (Ne) reductions in the cost-effective solution are made in agriculture. A cost-effective allocation of abatement measures entails that the nutrient reduction portions of the overall nutrient reduction are 3% (1%) in forestry and 97% (99%) in agriculture when the reduction target is set as 10% (30%).

We find that databases concerning the detailed costs of work items in preparing overflow fields and sedimentation ponds are still scarce, and additional data would be valuable. Furthermore, more research on the ability of the measures to reduce both nutrients and sediments is clearly needed. In the future, it is also important to assess whether permanent-like water protection structures would be needed in peatland forests, similar to mandatory buffer strips in agriculture. Current practice in forestry focuses on the use of water protection measures only infrequently. Recent studies indicate high chronic nitrogen and phosphorus exports from drained peatland forests, even when there have been no recent forest operations [37,75]. These exports are likely to constitute the bulk of nutrient

exports from forest land in peatland-dominated regions. If water protection structures were used continuously in peatland forests, forested areas would provide a much larger area for water protection than estimated in our river basin model. This would result in fundamental changes in cost-effective water protection policy in drained peatland-dominated areas, such as Finland.

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Appendix D. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wre.2019.100150>.

Appendix A. Second-order conditions in section 2

Section 2.1 Marginal abatement costs of nutrients in mineral soils

$$L_{TT} = (1 - m)pf_{TT}(T - A) - (1 - m)rf_{TT}(T - A) < 0 \quad A.1$$

$$L_{mm} = \lambda \left[\int_0^x g_{mm}(m)H(s) \right] < 0 \quad A.2$$

$$L_{\lambda\lambda} = 0 \quad A.3$$

$$L_{Tm} = L_{mT} = -pf_T(T - A) < 0 \quad A.4$$

$$L_{m\lambda} = L_{\lambda m} = \int_0^x g_m(m)H(s) > 0 \quad A.5$$

$$L_{T\lambda} = L_{\lambda T} = -r \left\{ \bar{z}_m - \int_0^x [1 - g(m)]H(s) \right\} = 0 \quad A.6$$

$$\bar{H} = -L_{TT}L_{\lambda m}^2 > 0 \quad A.7$$

In A.7, the bordered Hessian is positive, as required for the optimum.

Section 2.2 Marginal abatement costs of mitigating nutrient exports in drained peatland forests

The second-order conditions: Marginal abatement costs of nutrient exports in drained peatland forests

$$L_{TT} = pf_{TT}(T - A; n) - rf_{TT}(T - A; n) < 0 \quad A.8$$

$$L_{BB} = \lambda \left\{ \int_0^x g_{BB}(B)K_D(s, n) + \left[\int_0^x g_{BB}(B)K_C(s, n) \right] e^{-r(T-A)} \right\} < 0 \quad A.9$$

$$L_{\lambda\lambda} = 0 \quad A.10$$

$$L_{TB} = \lambda \left\{ r \int_0^x -g_B(B)K_C(s, n) \right\} < 0 \quad A.11$$

$$L_{B\lambda} = \int_0^x g_B(B)K_D(s, n) + \left[\int_0^x g_B(B)K_C(s, n) \right] e^{-r(T-A)} > 0 \quad A.12$$

$$L_{T\lambda} = r \int_0^x [1 - g(B)] K_C(s, n) > 0 \quad \text{A.13}$$

$$\bar{H} = 2L_{TB}L_{B\lambda}L_{T\lambda} - L_{TT}L_{B\lambda}^2 - L_{BB}L_{T\lambda}^2 > 0 \quad \text{A.14}$$

In A.14 we assume that the Lagrangian is concave enough to guarantee that the determinant of the bordered Hessian is positive, as required for the optimum.

Marginal abatement costs of mitigating sediment exports in drained peatland forests.

Consider a forest stand on a peatland adjoining a watercourse, as in section 2.2, but focus on the marginal abatement costs of sediments. Ditch cleaning causes sediment loads, which are expected to last for 10 years [2]. An overland flow field or sedimentation pond is used as a water protection measure to reduce the sediment load from ditch cleaning. Let the unit cost of ditch cleaning be w , while γ denotes the unit cost of the overland flow field/sedimentation pond. The size of the overland flow field/sedimentation pond is denoted by B . Let the sediment reduction target be \bar{q} . Ditch cleaning causes nutrient loading, $R(s, n)$. Sediment loading from ditch cleaning is expected to last for x years.

The Lagrangian function, L of the problem reads:

$$L = pf(T - A; n)e^{-r(T-A)} - wn - \gamma B + \lambda \left\{ \bar{q} - \int_0^x [1 - g(B)] R(s, n) \right\} \quad \text{A.15}$$

The first-order conditions of the maximization problem can be expressed as follows:

$$L_T = pf_T(T - A; n) - rpf(T - A; n) = 0 \quad \text{A.16}$$

$$L_B = -\gamma + \lambda \left[\int_0^x g_B(B) R(s, n) \right] = 0 \quad \text{A.17}$$

$$L_\lambda = \bar{q} - \int_0^x [1 - g(B)] R(s, n) = 0 \quad \text{A.18}$$

The first-order conditions of the maximization problem are as follows:

$$L_{TT} = pf_{TT}(T - A; n) - rpf_T(T - A; n) < 0 \quad \text{A.19}$$

$$L_{BB} = \lambda \left[\int_0^x g_{BB}(B) R(s, n) \right] < 0 \quad \text{A.20}$$

$$L_{\lambda\lambda} = 0 \quad \text{A.21}$$

$$L_{TB} = 0 \quad \text{A.22}$$

$$L_{B\lambda} = \int_0^x g_B(B) R(s, n) > 0 \quad \text{A.23}$$

$$L_{T\lambda} = 0 \quad \text{A.24}$$

$$\bar{H} = -L_{TT}L_{\lambda B}^2 > 0 \quad \text{A.25}$$

In A.25, the bordered Hessian is positive, as required for the optimum.

Appendix B. Sensitivity analyses

Table B.1

Marginal abatement costs (€ kg⁻¹): buffer zone. Nutrient reduction (% Ne), marginal abatement costs of nutrients (€ kg⁻¹ Ne), total cost (€ ha⁻¹), total costs (M €/year/ha shoreline). Timber prices (p) are 26 € m⁻³ and 43 € m⁻³.

Buffer zone						
Nutrient reduction, % Ne	Marginal abatement costs, € kg ⁻¹ Ne		Total cost, € ha ⁻¹		Total costs, M €/ha shoreline	
	p = 26	p = 43	p = 26	p = 43	p = 26	p = 43
8	257	424	82	136	1	2
10	360	595	140	231	2	4
15	663	1097	360	594	6	9
20	1024	1694	707	1170	11	18
25	1435	2374	1228	2031	19	32
30	1890	3126	1925	3184	30	49

Table B.2

Marginal abatement costs (€ kg⁻¹) of sediment: overland flow field and sedimentation pond. The interest rate is 2%, and the unit costs of the overland flow field and sedimentation pond change by 25%.

Marginal abatement costs, € kg ⁻¹				
Sediment reduction,	The costs of the overland flow field,		The costs of the sedimentation pond,	
%	-25%	+25%	-25%	+25%
20	0.001	0.002	0.011	0.018
30	0.002	0.004	0.018	0.029
40	0.003	0.006	0.025	0.041
50	0.006	0.010	0.032	0.053
55	0.008	0.013	0.036	0.060

Appendix C. The data used in the estimation of the marginal abatement costs of nutrients in agriculture

In the estimation of the marginal abatement costs of nutrients in agriculture, we used the data from a study by Lötjönen and Ollikainen [74], except that we converted the prices and costs to the 2016 price level [44]. The price of barley is 0.206 € kg⁻¹, the fixed cost is 216 € ha⁻¹, the variable cultivation cost is 134 € ha⁻¹ and the establishment and maintenance cost of the buffer strip is 103 € ha⁻¹. The price of nitrogen fertilizer is 1.90 € kg⁻¹. Conventional tillage is assumed, as it is the prevalent tillage method in Finland. The production of barley as a function of nitrogen fertilizer is:

$$P(N) = 5218 * (1 - 0.828 * \text{Exp}(-0.0168 * N)) \quad \text{C.1}$$

First, nitrogen runoff is modeled using the Simmelsgaard's nitrogen runoff function, where N denotes the fertilizer use and m_{BS} indicates the size of the buffer strip:

$$g(N, m_{BS}) = (1 - m_{BS}^{0.3}) * 15 * \text{Exp}(-0.7 + 0.7 * (N * (1 - m_{BS}) / 100)) \quad \text{C.2}$$

The parameters are calibrated to the Finnish agricultural conditions (for a more detailed description, see Lötjönen and Ollikainen [74]).

Second, the phosphorus runoff functions are based on studies by Uusitalo and Jansson [77] and Saarela et al. [78]. Particulate phosphorus runoff is a function of the size of the buffer strip and the phosphorus fertilization rate:

$$g_{PP}(P, m_{BS}) = (1 - m_{BS}^{0.3}) * 1.8 * (800 * (250 * \text{Log}[12.29 + 0.01 * P * (1 - m_{BS})] - 150)) * 10^{-6} \quad \text{C.3}$$

The dissolved reactive phosphorus runoff is calculated similarly as follows:

$$g_{DRP}(P, m_{BS}) = (1 - m^{1.3}) * 0.5 * (270 * (0.021 * (12.29 + 0.01 * P * (1 - m))) - 0.015) / 100 \quad \text{C.4}$$

Table C.1

Marginal abatement costs of nutrients (€ kg⁻¹): agriculture. Nutrient reduction (Ne, %), nutrient reduction (Ne kg ha⁻¹), the size of the buffer strip (% of the total area), nitrogen fertilizer application rate (kg ha⁻¹), marginal abatement costs of nutrients (€ kg⁻¹ Ne) and total costs (€ ha⁻¹) as the nutrient (Ne) reduction target varies from 8% to 30%.

Agriculture					
Nutrient reduction, % Ne	Nutrient reduction, kg ha ⁻¹ Ne	The size of the buffer strip, %	N fertilizer, kg ha ⁻¹	Marginal abatement costs, € kg ⁻¹ Ne	Total cost, € ha ⁻¹
8	2.00	0.03	122	0.34	0.18
10	2.50	0.06	121	0.55	0.39
15	3.75	0.19	119	1.26	1.47
20	5.00	0.44	116	2.29	3.68
25	6.25	0.86	114	3.67	7.41
30	7.51	1.51	111	5.42	13.06

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